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Enhanced Polymer Nanocomposites for Condition Assessment of Wind Turbine Blades

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ABSTRACT

Damages in composite components of wind turbine blades and large-scale structures can lead to increase in maintenance and repair costs, inoperability, and structural failure. The vast majority of condition assessment of composite structures is conducted by visual inspection and non-destructive evaluation (NDE) techniques. NDE techniques are temporally limited, and may be further impeded by the anisotropy of the composite materials, conductivity of the fibers, and the insulating properties of the matrix. In previous work, the authors have proposed a novel soft elastomeric capacitor (SEC) sensor for monitoring of large surfaces, applicable to composite materials. This soft capacitor is fabricated using a highly sensitive elastomer sandwiched between electrodes. It transduces strain into changes in capacitance. Here, we present a fabrication method for fabricating the SEC. Different surface treatment techniques for the nanoparticles are investigated and the effects on the mechanical and the electrical properties of the produced film are studied. Results show that using melt mixing fabrication method was successful at dispersing the nanoparticles without using any surface treatment, including coating the particles with PDMS oil or the use of Si-69 coupling agent. Yet, treating the surface would result in increasing the stiffness of the matrix as well as improving the interaction between the filler particles and the matrix.

Keywords: Strain gauge, soft capacitor, structural health monitoring, wind turbine blade, smart structures, capacitive-based sensor, sensing skin, smart materials

1. INTRODUCTION

Condition assessment of wind turbine blades involves careful examination and diagnosis of specific components to identify critical defects and damages that could compromise the overall structural strength. Currently, the vast majority of SHM of composite structures is conducted by visual inspection and non-destructive evaluation (NDE) techniques. NDE techniques, such as real-time X-rays, optical coherence tomography, Eddy current, and laser strain, have been thoroughly researched and evaluated [1-3]. The major disadvantage of these techniques is their temporal limitation, where they typically cannot be used for real-time (i.e. continuous) monitoring of large-scale systems. A solution is to utilize SHM techniques, which include sensing hardware that continuously measure structural states. In previous work, the authors have developed a novel sensing hardware to conduct continuous condition assessment of large-scale surfaces, which include wind turbine blades[4-6]. The sensing hardware consists of an array of soft-elastomeric capacitors (SECs), which behave as a sensory membrane capable of mapping two dimensional strains. Other bio-inspired materials have been proposed to conduct SHM [7-12].

The novel SEC proposed by the authors consists of three layers; a high permittivity dielectric elastomer sandwiched between two layers of highly conductive electrodes [4]. Nanoparticles were used as fillers in all the layers to enhance the permittivity and electro conductivity of the polymeric matrix. The capacitance of the film is defined by:

$$C = \varepsilon_0 \varepsilon \frac{A}{t} \tag{1}$$

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where C is the capacitance, ε_0 the vacuum permittivity ε is the permittivity of the elastomer, A the area of the electrodes, and t is the thickness of the membrane. Any change in the SEC geometry caused by a strain in the monitored structure will result in a direct change in capacitance.

The polymeric matrix of the SEC is fabricated from a styrene-based poly(styrene-ethylene/butylene-styrene) (SEBS) block copolymer filled with titanium dioxide (TiO_2). The dispersion of the TiO_2 fillers contributes to enhancing the physical and mechanical properties of the sensors. BCPs have shown better control on the spatial and orientation distribution of the ceramic nanoparticles when used for preparing nanocomposite dielectric materials[13]. Also, BCPs can be transformed easily into customizable geometries using conventional polymer processing techniques. The most common techniques used to produce sensor patches are solution cast and melt processing [14]. Both techniques can be used in large scale production of dielectric films.

The original fabrication method for the SEC is the drop-cast (or solution cast) technique. Fig. 1 illustrates the fabrication process of a SEC. The process is initiated by the fabrication of a SEBS/toluene solution. Part of this solution is used to create the nanoparticle mix, in which TiO_2 particles are added and dispersed using an ultrasonic dismembrator. The resulting mix is drop-casted on a glass slide, and dried over 5 days to allow complete evaporation of the solvent. Meanwhile, the remaining SEBS/toluene solution is used to create the compliant electrodes. Here, carbon black (CB) particles are added instead of TiO_2 to create a conductive mix. Finally, the CB mix is sprayed or painted on both surfaces of the dried polymer.

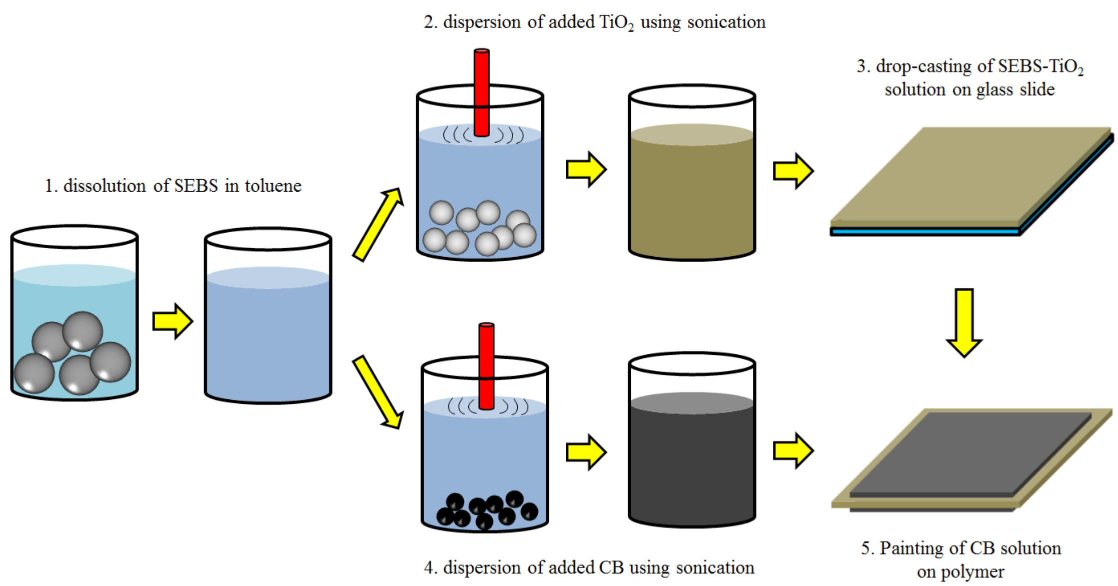

Fig 1: Drop-cast fabrication process [20]

The melt processing technique has been investigated by the authors [14], and research concluded the particle coating should be further investigated to ensure proper dispersion of the nanoparticles within the polymer matrix. The melt mixing fabrication technique is implemented as shown in Fig. 2. The process is done in two steps. First, the polymer and the filler are mixed in a twin-screw heated mixing chamber at 200 °C, 50 rpm. Second, the resulting mix is pressed into thin films at 200 °C, 3 psi. Fabricating the SEC using melt processing technique would have the added benefit of not requiring any solvent. This more sustainable process would reduce production cost and time in an industrial setup.

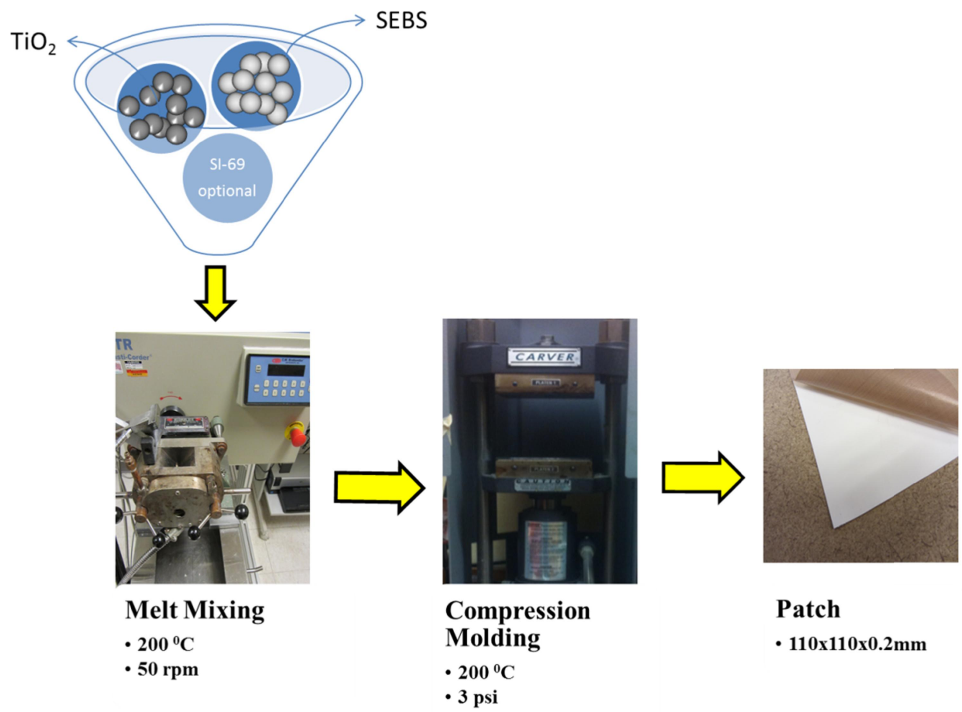

Fig 2: Melt mixing fabrication process

Despite unique advantages of using the TiO_2 fillers in SEBS, the non-polar nature of SEBS BCP limits the dispersion of polar TiO_2 particles in the polymer matrix. A solution is to graft polar functional groups in their case maleic anhydride on the SEBS backbone [15]. This chemical modification results in reducing negative interaction between the polymer and filler resulting in enhancing the reinforcement efficiency of the fillers. Similarly, the surface chemistry of the fillers is changed to attain fine dispersion of the fillers in the matrix. Kaynak et. al. [16] investigated the use of seven different saline coupling agents (SCA) to modify surfaces of the rubber particles. Several tensile and toughness tests were conducted. They concluded that some of the SCAs lead to an increase in strength with a decrease in the toughness. Ismail et. al. [17] studied the effect of adding saline coupling agent (Si-69) on the mechanical properties and the curing time of a natural rubber composite with bamboo fibre as a filler. The mechanical properties including tensile strength, tear strength, hardness and tensile modulus were improved.

In this paper, we further investigate the effects of surface treatment to the filler particles. The fabrication process of the nanocomposite will be done using the melt processing technique. Two different treatment methods are used; PDMS coating and Si-69 coupling agent. The morphology, permittivity and the mechanical properties are investigated.

The paper is organized as follows. Section 2 presents the experimental methods and techniques that are used to conduct the experiments. Section 3 presents and discusses results from the experiments. Section 4 concludes the paper.

2. EXPERIMENT

2.1 Material

The SEBS thermoplastic elastomer (TPE) used for preparing sensor films was purchased from VTC Elastoteknik AB, Sweden. The trade name of the materials is Dryflex 500120 (poly-styrene-co-Ethylene-Butylene-co-styrene) compounded with olefinic oil. The TiO_2 nanoparticles (density of ρ=4200 kg/m^3) with 300 nm size in the rutile crystalline phase is used as the uncoated filler, while the surface modified nanoparticles with poly-dimethylsiloxane (PDMS) surface coating is used as the coated filler. Both the coated and uncoated nanoparticles were purchased from sachtleben Chemie GmbH, Germany.

2.2 Fabrication Processes

The samples used for the experiments are listed in Table 1. They are designed to study the influence of chemical modification of the polymer matrix and nanoparticles on the dielectric and mechanical properties. The samples are prepared by blending TiO_2 nanoparticles into SEBS by melt mixing with a twin screw internal mixture from C.W. Brabender® Instruments, Inc., NJ. The amount of nano-fillers is adjusted to attain a volume concentration of 15 vol.% in all the samples. Similarly, modified SEBS polymer matrix is prepared by blending 5 ppm of Si-69 into the same twin screw compounder. The shear force applied on the sample while processing the twin screw internal mixture drives the dispersion of the nanoparticles inside the polymer matrix. The compounded samples are pressed into 110 × 110 × 0.2 mm films using a compression molding Machine from Carver, Inc, IN.

Table. 1 Testing smaples

Name	Content
pure	Pure SEBS films
un	Uncoated TiO_2+ SEBS
uncsi	Uncoated TiO_2+ SEBS+Si-69
coated	TiO2 particles coated with PDMS oil

2.3 Characterization

The morphology of the composite SEBS-TiO_2 nanoparticles is investigated by scanning electron microscopy (SEM) using a Hitachi S-2460N variable pressure SEM (VP-SEM) under helium atmosphere. The SEM images are collected at an accelerating voltage of 4, 8 and 20 kV and from a working distance of 25 mm. The SEM images are collected from the cryo-fractured surfaces prepared in liquid nitrogen (LN2). Mechanical properties are characterized by tensile testing using an Instron universal testing machine (model 5569) with a ±10 N load cell at room temperature (23 ± 2°C) and a rate of 50 mm/min. The tests are conducted on dog-bone samples to allow uniaxial deformation with a gauge length of 30 mm. The samples for the tests are prepared by stamping dog-bone shape specimens in accordance to ISO 527 type 5A. The relative permittivity of the films is measured after adding a layer of electrodes on the top and bottom of the films. The electrodes consist of 15% volume percentage CB (printex XE 2-B) in SEBS-Dryflex 500040. The capacitance of the sample is measured using a Sinometer 30-Range Digital Multimeter with Capacitance Measurement (MS8261) at a frequency of 40 Hz. The permittivity ε is calculated using Eq. (1).

3. RESULTS AND DISCUSSION

3.1 Morphology

A cryo-fracture is created using liquid nitrogen in a randomly selected location for each of the three films with nanoparticles filler. Fig. 3 shows the surfaces at magnification of 1500x and 5000x. The nanoparticles are expected to have a slightly ellipsoidal shape as revealed previously from SEM investigations [18]. They should also exhibit a highly anisotropic static dielectric[19].

Fig.3a to 3c corresponds to the SEM micrographs from cryo-fractured surfaces of investigated samples. The SEM micrographs depict fine dispersion of the nanoparticles in all the samples. However, the fractured surface morphology of nanocomposite with PDMS coated TiO_2 nanoparticles appear to show large clusters of nanoparticle agglomerations inside well dispersed nanocomposite phase. Similar agglomerations are found in composites when the particle-particle interaction dominates the particle-matrix interactions. However no agglomerations are found for both the no coating samples and the Si-69-surface treated samples (Fig.3 (b) and (c), respectively).

The shearing forces applied using the twin screw extruder can explain the dispersion results. These forces may have broken the particle-particle interaction forming the agglomerations, resulting in enhancing particle-matrix interaction and having a more uniform homogenous matrix.

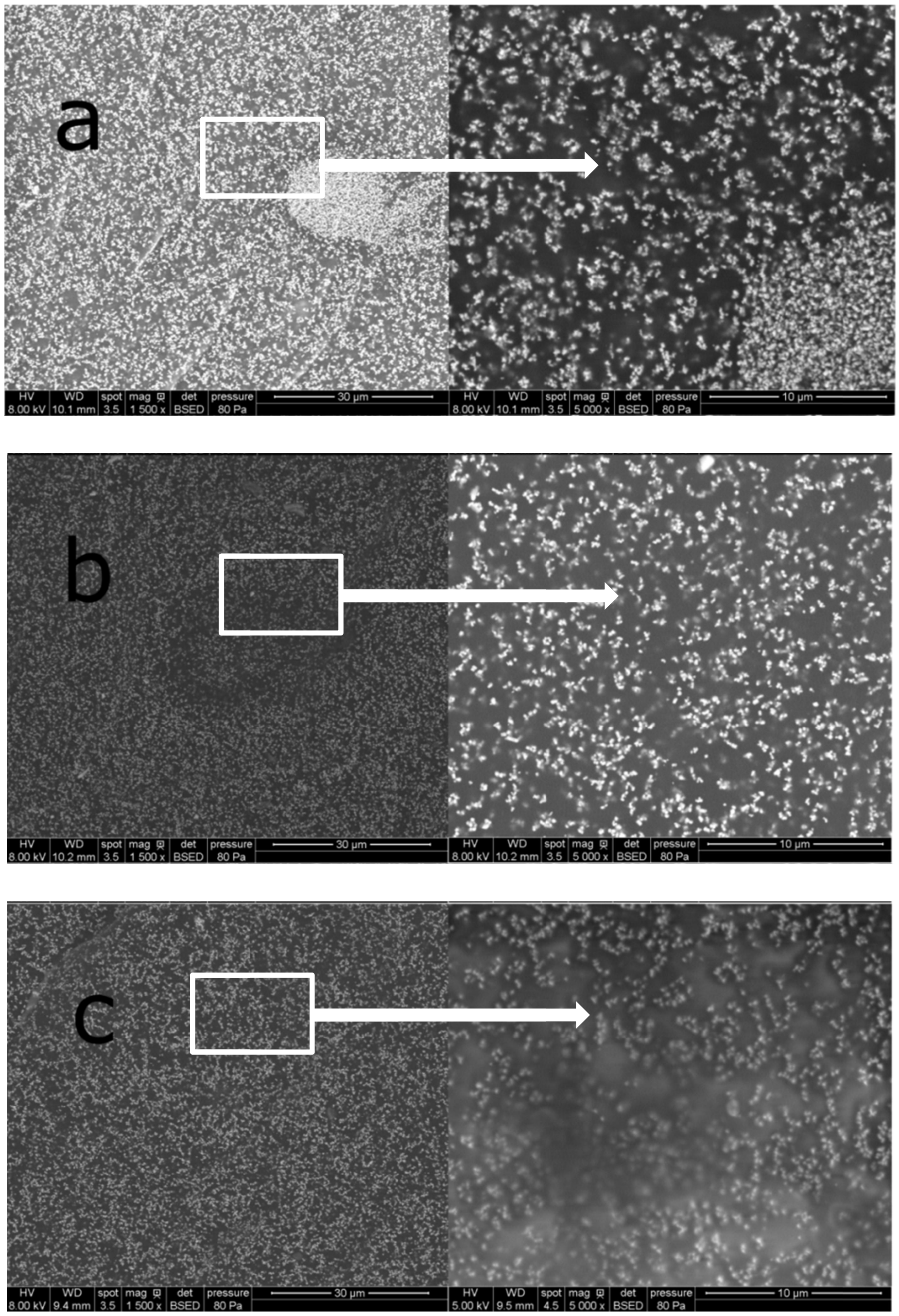

Fig 3. Fracture surface morphology of SEBS/ TiO_2 nanocomposites, a) coated, b) unc, c) uncsi

3.2 Permittivity

Table. 2 lists the results of relative permittivity calculated form Eq. (1). As hypothesized, the addition of the nanoparticles enhances the permittivity of the films. The coated particles (unc) resulted in the least enhancement; this is mainly due to the non-uniform dispersion of the nanoparticles in the polymeric matrix, as seen in Fig. 3. The permittivity enhancement induced by the addition of the uncoated particles represent an increase by 7% for the coated, 17% for the uncsi and 18% unc case, respectively. Adding Si-69 to the matrix does not appear to significantly affect the permittivity of the polymer, which shows that the Si-69 has little effect on the dispersion of the nanoparticles.

Table.2 Permittivity Analysis

Sample	Permittivity	% change wrt pure
pure	3.876	0
unc	4.574	18
uncsi	4.533	17
coated	4.145	7

3.3 Mechanical properties

Here, the tensile tests for all of the four films are performed. The engineering stress-strain curves are shown in Fig. 4. Young Modulus values are shown in Table. 3. The stress-strain profiles for all the specimens show an elastic response with yield strength less than 0.5 MPa and a high stretching capability before break which exceeded 600% of the original length.

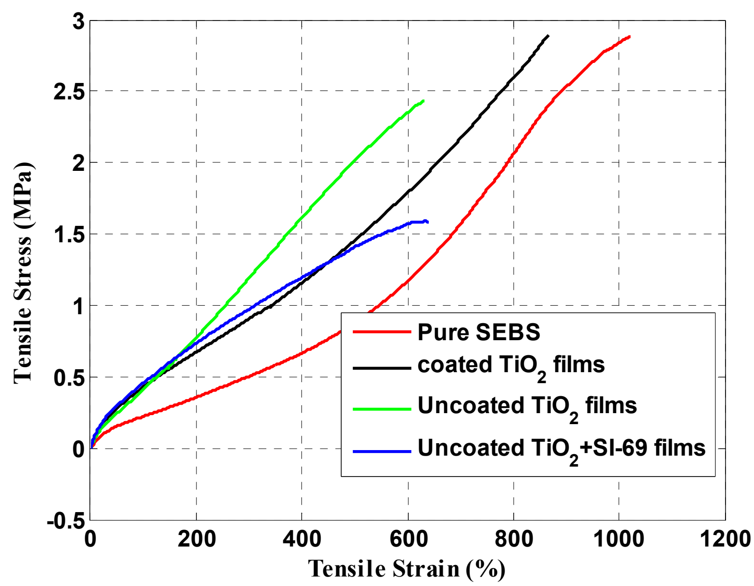

Fig 4. Stress-strain curves the presses films

Fig. 4 shows that treating the surface of nanoparticles affects the mechanical properties of the polymer. These changes are explained by an increase in the interaction between the nanoparticles and the polymer matrix. The curves show that the addition of fillers substantially increases the stiffness. The use of coated particles shows an increase in the stiffness of the processed nanocomposite accompanied by a decrease in the stretchability of the films. Using the uncoated nanoparticles results in increasing the stiffness and decreasing the ductility. The decrease in ductility can be explained by the weaker bonds between the polymer matrix and the filler particles. The use of Si-69 seems to have an adverse effect on the ductility, while improving stiffness.

Table.3 Young's Modulus of the processed films

Sample	Young's Modulus (MPa)	% change wrt pure
pure	0.221	0
unc	0.405	83
uncsi	0.454	105
coated	0.426	93

4. CONCLUSION

Soft nanocomposites made of TPE filled with ceramic particles were prepared to create SEC, for applications to wind turbine blades. We have investigated the melt-mixing fabrication technique for industrial manufacturization of the sensor. The melt-mixing process is seen as an improvement to the drop-cast process, as it has the potential to eliminate the presence of a solvent during the fabrication process. Two types of surface treatment were investigated to enhance the interaction between the nanoparticles and the polymer particles: 1) PDMS oil; and 2) saline coupling agent Si-69. The results showed that using the melt mixing technique resulted in a good dispersion of the uncoated nanoparticles and treating the surface did not have any significant effect on the dispersion. Conversely, treating the surface enhanced the particle matrix-nanoparticles interaction, resulting in an increase in ductility.

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